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Methods of Hydrogen Storage - An Introduction

This module gives an introduction to the attractiveness of Hydrogen as a fuel, as well as five methods to store hydrogen.

Methods of Hydrogen Storage for Use as a Fuel

Hydrogen is the first element listed in the periodic table, and is composed of one proton and one electron. Hydrogen is rarely found alone, as it readily combines with another hydrogen atom to form dihydrogen, H_2. Dihydrogen is a colorless and odorless gas at room temperature which is highly flammable, releasing a large amount of energy when combusted, i.e. the reaction is highly exothermic. As compared with combustion of the current fuels which operate automobiles, for example petrol, the energy released when hydrogen is combusted is more than three times greater.

Further, the combustion of octane, found in petrol, releases the greenhouse gas carbon dioxide into the atmosphere, and is not a "clean" fuel. When hydrogen is combusted in the presence of oxygen, however, the only product is water, as shown in the balanced chemical equation below.

$$2\ H2\ (g) + O2\ (g) \rightarrow 2\ H2O\ (g)$$

Both clean reactivity and the large chemical energy make H_2 extremely appealing for use as a fuel in automobiles.

If this method is so great, why has it not been implemented since the invention of automobiles? As stated, dihydrogen is a gas at room temperature. Gases, compared to the other states of matter (liquid and solid), occupy the most volume of space, for a given number of molecules. Octane and other hydrocarbons found in gasoline are liquids at room temperature, demanding relatively small fuel tanks. Liquids are therefore easier to store than compressed gases. A modern vehicle can travel about 400 km on a full tank of gasoline (24 kg). To cover the same range, 8 kg of hydrogen is needed, or even as low as 4 kg for a hybrid car with a fuel cell.

H_2 has a high energy content per weight (more than three times as much as gasoline), but the energy density per volume is rather low at standard temperature and pressure. Volumetric energy density can be increased by storing the gaseous hydrogen under increased pressure or storing it at extremely low temperatures as a liquid. Hydrogen can also be adsorbed into metal hydrides and highly porous materials. The current available methods of storing hydrogen include compressed hydrogen and liquefied hydrogen, however many promising methods exist, namely metal organic materials (MOMs), metal hydrides and carbon nanostructures.

Department of Energy Hearing on the Methods of Hydrogen Storage for Use as a Fuel

This module serves as the imaginative public hearing hosted by the U.S. DOE in the case study "Methods of Hydrogen Storage for Use as a Fuel".

Department of Energy Hearing on the Methods of Hydrogen Storage for Use as a Fuel

Welcome, everyone to the "Methods of Hydrogen Storage for Use as a Fuel" hearing. We, the Department of Energy, have invited you all here because we believe that there exists five very promising technologies which can be used to store and transport hydrogen safely and effectively, and we would like to ultimately decide which method is the most realistic for near future implementation. In front of me there are five panels, each representing a specific method of storage. I must note that while this hearing is open to the scientific community, we will not be accepting any questions or comments. I trust that you have read the background information sheet titled "*Methods of Hydrogen Storage*", and understand the purpose of this hearing. Without further ado, I would like to introduce our five panels, numbered according to the order in which they will present their defense: Panel 1 represents storing hydrogen as a compressed gas, Panel 2 represents liquid hydrogen, Panel 3 represents metal organic materials, Panel 4, metal hydrides, and lastly, Panel 5 represents carbon nanostructures.

Each panel will present and defend their method of storage, including its pros, as well as cons. I encourage each panel to take note of the other's defense, as a controlled debate will follow Panel 5's presentation. Our main DOE panel will serve as mediators throughout this hearing, and will voice our overall consensus at closure.

Panel 1, we will begin with you, please organize your defense and begin your presentation when appropriate.

Compressed Hydrogen Fact Sheet

This module contains the fact sheet relevant to compressing hydrogen gas for storage.

Compressed Hydrogen Fact Sheet

Compressing gas is the process of applying an external force which minimizes the distance between gas particles, therefore forcing the system to occupy less volume. This is attractive since many particles can exist in a reasonably sized tank. At room temperature and atmospheric pressure, 4 kg of hydrogen occupies a volume of $45m^3$, which corresponds to a balloon with a diameter of 5m. Clearly compression is required to store and transport the gas. When it comes to individual mobility however, these tanks are still far too large for the average sized automobile.

Compressed tanks are regularly filled to 200 atmospheres in most countries. Storing 4 kg of hydrogen still requires an internal volume of 225 L (about 60 gallons). This amount can be divided into 5 tanks with 45 L internal volume.

Evacuation of the gas for combustion would be rather simple, a simple valve could regulate the flow of hydrogen. While this method could be feasible for cars, it is more likely that gases will be compressed for transport and not for use in individual vehicles.

Liquid Hydrogen Fact Sheet
This module contains facts related to storing hydrogen as a liquid.

Liquid Hydrogen Fact Sheet

Liquid hydrogen is made possible by cryogenically cooling it to below its boiling point, -253°C. As a liquid, the same amount of gaseous hydrogen will require much less volume, and therefore is feasible to individual automobile use. A refrigeration system is required to keep the liquid cooled, for if the system temperature rises above hydrogen's critical point (-241°C), the liquid will become a gas. There must exist a vacuum insulation between the inner and outer walls of liquid hydrogen tank system, for heat cannot travel through a vacuum. There is a tradeoff, however, because the tank must be an open system to prevent overpressure. This will lead directly to heat loss, though minimal.

The relative tank size has a broad range, with small tanks having a volume of 100 L, and large spherical tanks sizing all the way up to 2000 m^3. Refrigeration systems are not a likely feature for every automobile, and open systems may pose a hazard should an accident occur. Cooling hydrogen down to a liquid is a convenient method of storage, however, and its implementation most likely will be limited to large stationary tanks as well as mobile multi-axle trucks.

Metal Organic Materials Fact Sheet

This module contains a fact sheet related to metal organic materials.

Metal Organic Materials Fact Sheet

Metal organic materials, also referred to as metal organic frameworks (MOFs) are a unique class of solid state materials which exhibit potential to be used for the storage of gases. As its name suggests, these structures assemble themselves into frameworks, much as buildings are constructed from steel frameworks. Inorganic metal clusters compose the edges of the framework, while organic molecules link the clusters together. A variety of organic linkers may be used, allowing the structure to be tunable.

Image courtesy of Dr. Mohamed Eddaoudi at the University of South Florida, Department of Chemistry

The 3-D framework naturally has pores which capture gas particles. The process of capturing is known as sorption. Hydrogen, being a gas, will adsorb into the framework and "stick" throughout it, much as water is held in a sponge. There are two main methods of adsorption, physisorption and chemisorption. Gas particles are physisorbed when the force that holds the particle in place is Coulombic, meaning static forces are involved in bonding. On the other hand, the particles are considered chemisorbed when covalent bonds are made between the gas and the framework, exhibiting a stronger bond. The greater the interaction of particles with the framework, the more overall particles may be sorbed, and the smaller volume the framework needs to occupy. The majority of current MOFs physisorb gases, however, and one of the main research efforts at this point is to target MOFs which chemisorb gases.

Once maximum sorption (equilibrium) is reached, the gas will remain attached to the framework, and evacuation may be performed when desired. Evacuating the gas is as simple as applying heat to the system. Although the gas will be released first, it is almost inevitable that the framework will collapse as well. Additional research efforts are underway to enhance framework strength.

Carbon Nanostructures Fact Sheet
This module contains facts relevant to carbon nanostructures.

Carbon Nanostructures Fact Sheet

Carbon nanostructures are exactly as their name implies, a nano-scale (10^{-9} m) structure made exclusively of carbon atoms. It was originally cited that single-walled carbon nanotubes displayed the property of capturing hydrogen, however recent efforts to replicate the results have been difficult. It is known, however, that doping the nanotube with a metal will have a profound effect on capturing hydrogen[2]. The key benefit of this storage technique is the availability of reversible binding at room temperature.

While these structures cannot capture as much hydrogen as the DOE goals require, many research efforts are being made to tune these structures so as to store a greater amount to hydrogen gas. Carbon nanotubes are a relatively new technology and therefore efforts must be made to drive down the cost of producing these tubes. Nanotubes are a promising method of gas storage, and will most likely find application in vehicles.

Image courtesy of Dr. Mohamed Eddaoudi at the University of South Florida, Department of Chemistry

[2] U.S. Department of Energy. http://www1.eere.energy.gov/hydrogenandfuelcells/storage/carbon_materials.html

Metal Hydride Fact Sheet

This module contains the fact sheet related to metal hydrides.

Metal Hydrides Fact Sheet

Metal hydrides are coordinated complexes and/or crystal systems which reversibly bind hydrogen. The hydrogen is favorably incorporated into the complex and may be released by applying heat to the system. A major method to determine a particular complex's effectiveness is to measure the amount of hydrogen that can be released from the complex, rather than the amount it can store.

Some issues with metal hydrides are low hydrogen capacity, slow uptake and release kinetics, as well as cost.[1] The rate at which the complex accepts the hydrogen is a factor, since the time to fuel a car should ideally be minimal. Even more importantly, at the current stage of research, the rate at which hydrogen is released from the complex is too slow for automobile requirements[1].

This technology is still a very promising method, and further research allows for the possibility of highly binding and rapid reversal rates of hydrogen gas.

[1] U.S. Department of Energy. http://www1.eere.energy.gov/hydrogenandfuelcells/storage/metal_hydrides.html

The Most Promising Storage Method - Hypothetical

This module contains the final document used in the case study "Methods of Hydrogen Storage for Use as a Fuel".

The Most Promising Storage Method

Thank you all for your informative presentations. We have come to understand much about the methods of storing hydrogen. It seems appropriate not to completely invest solely in one technology, as each method has its benefits as well as drawbacks.

Compressed hydrogen is a reasonable method for long term storage, as it requires no energy to maintain compression. It does seem unlikely, however, that each automobile have a compression system and large volume tanks on board.

Liquid hydrogen is also very feasible for storage, as it demands less volume than gaseous hydrogen. There is a large maintenance fee to keep a refrigeration system constantly running, so automobile implementation is not so likely as well.

Concerning the methods not currently available, yet very promising, all three are likely to be the standard method of storage in individual vehicles, though novel breakthroughs in research must be made before their wide scale debut. It cannot be predicted which technology will breakthrough first, though we must remain persistent in our research efforts, as the importance of alternative fuels and clean energy cannot be stressed enough.

It is imperative that no one method be considered superior and others excluded, as each storage method is unique and beneficial in its own regard. On behalf of the U.S. Department of Energy I would like to thank you for joining us today, and have a pleasant afternoon.

Hydrogen Storage Case Study Teacher Notes
This module contains the Teacher Notes for the Hydrogen Storage for Use as a Fuel Case Study.

H 2 Storage Teacher Notes

Introduction/Background

This case study will be concerned with the methods currently available to store hydrogen for use as a fuel. The main format of presentation will be "public hearing." This hypothetical hearing will be hosted by the Department of Energy and each panel will be proposing their method of storage to the DOE. Since each panel will represent a specific storage technology, the class will be divided into five groups, each defending their own method. Further debate will follow. Additional information, including time limits for each step of the case, can be found under the heading *Classroom Management*, found within this document.

The first step in this case study, is to read the introductory document titled "*Methods of Hydrogen Storage*." This introductory text explains the theory of using hydrogen as a fuel and briefly introduces five promising methods for storing hydrogen. In order to fully understand this material, students should have a basic understanding of general chemistry. While not required, a course taken in basic physics will be beneficial for a deeper level of understanding.

No prior knowledge of the methods of storing hydrogen or the idea of using hydrogen as a fuel is needed. In fact, it is a major objective of this study for students to critically analyze material they have no prior knowledge of and defend it as if they were experts.

This case study is written to conform to the decision or dilemma case type, as students are to defend their method of storing hydrogen and formulate a decision as to which method deems the most appropriate as it applies to using the hydrogen as a fuel for automobiles. In terms of teaching this case, as mentioned above, a public hearing format is used. The hearing is hosted by the Department of Energy (the instructor must play this role), and the students act as the panels which present their method of storing hydrogen.

Objectives of the Case

Each group of students, representing a specific method of storing hydrogen, will be given a handout which introduces them to the technology and includes pros and cons. The students are then required to extract vital information from the text in order to formulate a defense. This forces the students to analyze scientific information, rather than strictly be handed facts to memorize. Students must orally present their defense, allowing them to internalize the material, since they are teaching the rest of the class about their technology.

Later in the case, students will be asked to form their own opinion of the most reasonable storage method for individual automobile use. The intention of this step is to recall the information learned from the other panels and allows them to form a personal opinion, without being restricted to one storage method.

Classroom Management

The first step towards initiating this case study is to read the *Methods of Hydrogen Storage* document aloud. This will introduce the class to the basic chemistry of molecular hydrogen, the attractiveness towards its use as a fuel, and the five most reasonable methods to store and transport hydrogen.

After this document is read and understood, the class should be divided equally into five groups. Once in groups, the "*DOE Hearing on the Methods of Hydrogen Storage for Use as a Fuel*" document should be read aloud to the class. This document states the purpose of the meeting, sets the scene, and gives an overview of how the rest of the case study will proceed. The briefing will introduce the students to the benefits of using hydrogen as a fuel and the various methods of storing it.

After the initial briefing, each group will obtain a unique handout which introduces them to "their" technology. Written in paragraph form, students are required to analyze the writing in order to identify key information. Ten to fifteen minutes will be granted for each group to read the information sheet and collaborate with each other to structure their defense. Students should be encouraged to express

creativeness in their defense and should not solely quote the facts extracted from the information sheet. Each group will then have five to ten minutes to present their case, defending their method. The instructor will play the role of the DOE, and will serve as the mediator to monitor each presentation. Debate between each group will be allowed, should it occur at this stage, but not encouraged.

After the final defense, the class should be asked, as a whole, which technology is best in their own opinion, no longer being restricted to their assigned technology. These questions may be located in the *Questions in the Classroom* section which follows. Debate here is encouraged. The time allowed for individual opinion/debate may vary based on class time, while extension to another class period is acceptable. Students are encouraged to think critically and encompass the facts into their opinions.

To end the case study, the instructor (posing as the DOE) should state the overall consensus for the best technology. After this, the most promising technology should be stated, backed by scientific facts, and can be found in the document *The Most Promising Storage Method*.

Questions in the Classroom

Following Panel 5's defense, the class should be asked which storage method is the most probable for individual vehicle implementation. Allow the students to debate with each other, should it occur. Ensure that their opinions are valid and have scientific backing.

Background Sources

All metal organic material information is derived from the University of South Florida, and can be located at http://chemistry.usf.edu/smmartt/research/eddaoudi/.

Much information about hydrogen storage in general, as well as specific methods was taken from the U.S. Department of Energy's Hydrogen, Fuel

Cells & Infrastructure Technologies Program webpage: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/index.html. Please reference this page for further information.